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Resolving the generation mechanisms and electrodynamical effects of Medium Scale Traveling Ionospheric Disturbances (MSTIDs)

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The term “Medium-Scale Traveling Ionospheric Disturbances” is used to describe a number of different propagating phenomena in ionospheric plasma density with a scale size of hundreds of km. This includes multiple generation mechanisms, including ion-neutral collisions, plasma instabilities, and electromagnetic forcing. Observational limitations can impede characterization and identification of MSTID generation mechanisms. We discuss inconsistencies in the current terminology used to describe these and provide a set of recommendations for description and discussion.

KEYWORDS

ionosphere, thermosphere, geospace, traveling ionospheric disturbances, space weather, plasma density, MSTID generation mechanisms

1 Introduction

Medium Scale Traveling Ionospheric Disturbances (MSTIDs) have been observed in ionospheric measurements since the 1950s (Munro, 1950). In the simplest observational terms, MSTIDs are exactly as described–propagating disturbances in ionospheric plasma density and have a characteristic scale size (single- or multi-peaked wavefronts) on the order of hundreds of km. MSTIDs are important because they can have a large impact on communication and navigation signals. Several operational communication systems are influenced by the ionosphere, particularly High Frequency (HF) systems, which reflect off the ionosphere like a mirror. Large temporal and spatial gradients in the F-region plasma density can negatively impact operational radio systems (e.g., Goodman, 2005). As the number of observations has rapidly increased in the literature over the years, our understanding of MSTIDs has improved and it is now believed that this term describes phenomena with varying generation mechanisms, propagation tendencies and electromagnetic properties. Thus, while the term "MSTID" may be a useful description of the observations, it can be used to describe a wide range of actual physical processes that are not all necessarily connected. The goal of this paper is to discuss the varying aspects of MSTIDs and present classification recommendations to improve the communication amongst the research community.

Throughout the literature there is significant variation in the basic observed properties of MSTIDs, which may be partially due to constraints in current observational techniques. For example, the actual definition of what "medium-scale" is varies among different authors. Generally, papers discussing MSTIDs include a range of horizontal wavelengths on the order of hundreds of kilometers (e.g., Hunsucker, 1982), with the upper limit set anywhere from 300*km* (Cheng et al., 2021) to thousands of *km* (Figueiredo et al., 2018). Some authors have considered only waves on the order of about 100 km to be MSTIDs (Kil and Paxton, 2017). It is worth noting that observations capturing only a one-dimensional slice of the wave may set a larger upper limit, since the slice is not guaranteed to be aligned with the direction of propagation or the wave vector. In this case, a longer wavelength is observed, which is projection of the original wavelength along the observation direction and is sometimes referred to as a virtual wavelength. For the purposes of this paper, we will be focused on periodic ionospheric perturbations with wavelengths of 100–1,000 km and periods of 15–60 min. We should note that this classification simply divides small, medium, and large scale TIDs based on scale with small in the 10s of km, medium in the 100s of km and large in the 1000s of kms. It does not reveal anything about the generation or nature of these TIDs. This definition may need to be reconsidered in the future as there can be an overlap between driving mechanisms across scale sizes.

Another area where observational limitations may contribute to MSTID classification is in the definition of "nighttime" MSTIDs also often described as "Electrified MSTIDs." It is often assumed that "nighttime" MSTIDs are associated with large polarization electric fields and generated by the Perkins instability combined with E/F region coupling. However, a number of observations have demonstrated the existence of nighttime MSTIDs generated by other sources such as Atmospheric Gravity Waves (AGWs) from Tropospheric weather and the solar terminator (e.g., Azeem et al., 2015; Galushko et al., 1998). To confuse matters even more, some MSTIDs that are associated with Atmospheric Gravity Waves (AGWs) have been shown in theory and observations to have an electric field component (e.g., Huba et al., 2015; Jonah et al., 2018). Other observations have shown a combination of dynamics and electromagnetics at play during large geomagnetic storms (Chimonas, 1974; Habarulema et al., 2022). As different types of MSTIDs may have electric field components, the term "Electrified MSTID" is not particularly useful for categorizing this type of MSTID.

The community has made substantial progress in better understanding MSTIDs in the past few decades. While significant work is still being done, a number of the remaining major problems in understanding MSTIDs rely on better communication within the research community. Specifically, classification recommendations could assist in clarifying communication between the researchers to more quickly make progress on investigating the nature and dynamics of MSTIDs. For example, observational scientists may not always be able to distinguish the generation mechanism of an MSTID from observations alone, but in some cases a mechanism is assumed. This leads to confusion in better understanding the physical processes responsible for MSTID generation. The following sections of this paper outline some of the outstanding problems in understanding MSTIDs; an overview of some current issues with MSTID classification and finally a series of recommendations for classifying MSTIDs.

2 Outstanding problems

Many questions remain about the generation, propagation, and effects of MSTIDs. A recent paper describes many of the outstanding problems for TIDs driven by Atmospheric Gravity Waves (AGWs) (Zawdie et al., 2022). While the Zawdie et al. (2022) paper describes questions related to AGW driven TIDs, there are also remaining questions about other types of TIDs. One major issue in TID studies is that it is difficult to obtain a full 3D picture of the perturbation in the ionosphere due to measurement limitations. One way this may be mitigated is by combining disparate observations. For example, GPS TEC measurements obtain a 2D latitude/longitude picture of the TID, but adding ionosonde or ISR measurements in this region can provide some information on the vertical structure of the TID. The following list includes oustanding questions not discussed in Zawdie et al. (2022).

- What is the relationship between neutral atmospheric waves and MSTIDs? While MSTIDs are often attributed to be the manifestation of atmospheric waves (including gravity waves, acoustic waves, infrasound), the exact relation between MSTID and the neutral atmosphere has not been well studied, in part due to lack of neutral atmospheric measurements. Observations from DE2 show a phase lag between the ion and neutral waves below 300 km altitude (Earle et al., 2008).
- Under what conditions do instability processes generate an MSTID? While instability mechanisms may be enhanced by electromagnetic coupling between the E and F-region ionospheres in both hemispheres, the full range of conditions and requirements for MSTID generation are not understood. Yokoyama (2014) and Narayanan et al. (2018) have shown

both theoretically and experimentally that sporadic E is more essential than favorable winds for the formation of instability-driven MSTIDs. This is further supported by observations over Northern Germany by Sivakandan et al. (2022) and over Japan by Fu et al. (2022).

- How effectively do the electric fields generated by instability-driven MSTIDs map to the conjugate hemisphere relative to MSTIDs generated by other mechanisms? There is some evidence that AGW driven MSTIDs generate electric fields and conjugate effects (e.g., Huba et al., 2015; Chou et al., 2022; Shinbori et al., 2023). We might expect these fields will be different in magnitude or mapping efficiency with the instability type having a larger magnitude based on preliminary simulation work, but this has not been rigorously examined.
- Are there observational measurements that would enable us to determine the generation mechanism of an MSTID? We believe that there are multiple generation mechanisms for MSTIDs, but it is currently unknown whether these create fundamental differences in the MSTID that could be measured. For instance, if the electric fields generated by AGWs and Instabilty MSTIDs are different, then measurements may be able to distinguish between them. The relative lag between perpendicular and parallel ion flow relative to geomagnetic fields may also produce different signatures (e.g., Klenzing et al., 2011; Miller et al., 2014).
- How well does the Hooke model reproduce the shape of MSTIDs in the ionosphere? Hooke (1968) derived an analytical representation of a MSTID perturbation in the ionosphere using a simplified description of an atmospheric gravity wave as a driving mechanism. Due to a lack of 3D measurements in the ionosphere the accuracy of this representation is not known.
- Are there daytime MSTIDs with a large electric field component? General consensus is that the daytime E-region ionosphere has a larger conductivity that would suppress any electric fields arising out of instabilities. However, there are some observations of possible co-occurrence of MSTIDs in conjugate regions during the daytime, implying mapping of electric between hemispheres (Jonah et al., 2017).
- How can multiple potential generation mechanisms be separated if simultaneously present? MSTIDs are believed to have sources originating both in the lower atmosphere (below) and the sun (above), but in some cases these sources are present simultaneously (e.g., Earle et al., 2010). Given sufficient spatially separated measurements, these different energy paths have been separated previously (e.g., Verhulst et al., 2022).

3 Observations and limitations

MSTIDs are observed with many types of instruments that can be roughly separated into three categories:

1. Point observations from a location forming time series from a single height or a vertical profile like those of iso-electron density contours from ionosondes, VHF radar and incoherent scatter radar echo profiles, airglow photometer measurements, GNSS TEC time series from a single location, radio telescope observations (e.g., Jonah et al., 2017; Negale et al., 2018; Mangla and Datta, 2023). Such measurements typically provide the periods and amplitudes of MSTIDs. Sometimes, multiple points can be observed, for example, with a beam steering radar. Multiple spatially separated observations can help determine horizontal propagation direction.
2. Observations over an area made by airglow imaging, GNSS TEC maps, SuperDARN radar scans, space based imaging observations (e.g., Tsugawa et al., 2007; Frissell et al., 2014; Rajesh et al., 2016; Narayanan et al., 2018). These measurements do not provide physical parameters like temperature or wind perturbations in general.
3. *In-situ* ionospheric measurements made by sounding rockets and satellites like CHAMP and SWARM that are intermittent both in space and time (e.g., Shiokawa et al., 2003; Park et al., 2009). Because of their intermittent nature, these are suitable for statistical studies or need to be combined with other measurements to make meaningful observations about MSTIDs. However, they provide direct measurement of required physical parameters.

Note that none of these techniques alone provide all the necessary physical parameters to deduce the origins of the MSTIDS or their three-dimensional structure.

Compared to the abundance of ion measurements, we lack routine measurements of neutral parameters in the thermosphere. This complicates the identification of the true nature of MSTIDs and their causative forcing. When such measurements are available, it is possible to identify those MSTIDs generated by co-existing thermospheric gravity waves. In the absence of such measurements, it is difficult to separate MSTIDs that are driven by electrodynamic instabilities vs. neutral atmospheric forcing. For example, MSTIDS in the midlatitude night time region may be driven by polarization electric field driven through the E-F region electrodynamical coupling (Cosgrove and Tsunoda, 2004) or by co-existing thermospheric gravity waves (Earle et al., 2008). Therefore, merely describing a particular MSTID event as resulting from a specific generation mechanism without multi-parameter observations and investigation is somewhat arbitrary. A new generation of coincident thermospheric and ionospheric measurements are needed to resolve these problems. Missions on the NASA and ESA roadmap that could help constrain these questions are the Geospace Dynamics Constellation (Jaynes et al., 2019) and EN-LoTIS (ESA/NASA, 2024). Additionally, new geographically disperse ground based measurements such as TechTIDE (Belehaki et al., 2020) and the Chinese Meridian Project (Wang et al., 2024) are being constructed and expanded, offering new possibilities.

4 Classification suggestions

One of the difficulties in achieving closure on many of the above questions is that MSTIDs are not a single thing, but they actually have many different potential generation mechanisms and propagation characteristics. Quantifying the difference between these different types of MSTIDs is essential to answer many of these remaining scientific questions. Moving forward, it is essential to refine and standardize the terminology used to refer to these characteristics to improve communication between researchers using different data sets and methodologies. Clear communication is a prerequisite for resolving open questions.

In order to address these challenges, a multi-faceted approach is suggested. It is important to distinguish between the driving mechanisms and the characteristics. We encourage authors to include a paragraph on MSTID classification in their research articles and letters nominally based on the following considerations.

4.1 Observables

- Include key observables such as wavelength, propagation, etc.
- Be clear on the observed physical parameters (density, fields, etc.).
- Limitation of observational techniques should be discussed when possible.
- Seasonal and local time conditions.
- Solar and geomagnetic activity.
- Caution should be used with the term "Electrified." We note that electrodynamic structure is an observational property potentially resulting from multiple driving mechanisms. If electric field information is available, this is valuable information.
- For conjugate MSTIDs, there is both a primary MSTID and an image MSTID in the conjugate hemisphere. Depending on the available observations, it can be difficult to distinguish between the primary and the image.
- The presence of nearby larger scale TIDs should be noted as well, since these may provide clues to generation mechanisms.

4.2 Potential driving mechanisms

- Collisionally driven–primarily driven by mechanical forcing through ion-neutral coupling. This includes acoustic wave and AGW driven MSTIDs. When able to identify a specific source (e.g., Tropospheric weather, geomagnetic storm, volcanic eruptions), include this.
- Instability driven–primarily driven through electrodynamic forcing in the E-region or F-region. Subsets include Perkins instability, electric field coupling between the E– and F-regions, potentially aided by sporadic-E, coupling. Note that a conjugate image MSTID may be electrodynamically driven by the electric fields imposed from the conjugate hemisphere, but the primary MSTID may be driven through collisions (e.g., Chou et al., 2022) or electrodynamics (e.g., Otsuka et al., 2004).
- Solar radiation driven–includes enhanced ionization in regions of enhanced neutral density as in Hooke (1968), as well as due to increased radiation from solar flares (e.g., Pawlowski and Ridley, 2008; Zhang et al., 2019).
- Note that multiple mechanisms may also act independently. For example, observations over Europe after the Hunga-Tonga volcanic eruption noted multiple types of TIDs propagating, including those that occur from concurrent geomagnetic storms (Verhulst et al., 2022).
- If the driving mechanism is unknown, it is worth stating up front. This can help identify and organize future studies and campaigns.

5 Summary and conclusion

There is understandable desire in the community to separate and categorize MSTIDs into different types. The primary example is the 'EMSTID', which is often used to describe mid-latitude MSTIDs with a preferred propagation direction and orientation. As discussed in this work, however, 'Electrified' may not be unique to this type of MSTID, so is not the best term for classification. We suggest that current MSTID categories are insufficient. Instead, we recommend that papers on MSTIDs address their physical properties and potential generation mechanisms as a section in the paper. This will provide clarity about the research conclusions, reduce confusion about open questions, and ensure appropriate use of the results and observations in future work.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

JK: Conceptualization, Writing–original draft, Writing–review and editing. KZ: Conceptualization, Writing–original draft, Writing–review and editing. EA: Writing–review and editing. AnB: Writing–review and editing. MB: Writing–review and editing. AgB: Writing–review and editing. CF: Writing–review and editing. NF: Writing–review and editing. WF: Writing–review and editing. DH: Writing–review and editing. JH: Writing–review and editing. PI: Writing–review and editing. SK: Writing–review and editing. VN: Writing–original draft, Writing–review and editing. MS: Writing–review and editing. JS: Writing–review and editing. CX: Writing–review and editing. TY: Writing–review and editing. MZ: Writing–review and editing. S-RZ: Writing–review and editing.

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Conflict of interest

Author JH was employed by Syntek Technologies Inc. Author PI was employed by Computational Physics Inc.

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